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Additive Manufacture of Propulsion Systems in Low Earth Orbit

by

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Abstract

Lifting mass to orbit is one of the most challenging concepts of space travel. This paper proposes a concept of a Hub at the low earth orbit (LEO) that additively manufactures (AM) or more colloquially 3-D prints components of the boost and satellite systems in order to reduce weight to orbit. A Hub at LEO with three components modules will accomplish this, and estimates put the cost for this effort around that of one government satellite launch. This concept proposes a receive/assemble/deploy module to capture a satellite as it boosts from Earth then attaches AM parts to the satellite for redeployment, a print module to print RL-10 like boost phase engines and multi-mode propulsion systems, and a storage facility for materials and propellants. This Hub will enable making parts by AM parts in space, leading to the printing of more complex systems in the future, which will promote the development of space exploration into the future.

Revolutionary Aspects of in-Orbit Additive Manufacturing

1. Enabling Capabilities

The future of launch is ever developing. Commercial companies are charging ahead to reduce the costs of mass to orbit. This proposal posits that printing a boost phase engine and satellite propulsion system on orbit would allow for great mass to orbit via a Hub in a low Earth orbit (LEO) with an additive manufacturing (AM) printing capability. Second stage boost engines would be printed, as well as the tanks and propulsion system for the satellite. Robotic technology with optional "human-in-the-loop" access would assemble any large parts. These are the parts outside the on-orbit printer capacity, or complex parts which require welds due to material or stress requirements.

2. Printing an upper stage boost and satellite propulsion system

The ideal propulsion system to boost a satellite to operational orbit would be an engine with performance similar to the RL-10 due to its reliability since the 1960s and its high thrust levels. A photo of the RL-10 for reference is Figure 1. The RL-10 is an example of an operational upper-stage engine that is most mature in AM parts and hot fired tests by NASA Marshall.[2] SpaceX has recently revealed that 40% of their Raptor 2 next generation engine has been printed.[3] Blue Origin has shown a print of their oxidizer turbopump for their BE-4.[4] Additionally, United States contractor Aerojet Rocketdyne has shown multiple parts of their liquid engine fleet to be printed, including a pogo accumulator and a turbopump.[6] Printing turbopumps shows some of the most

Figure 1: RL-10 Engine[5]

advanced AM so far due to the complex nature of the machinery. Applying this technology to future rocket propulsion solutions on orbit is critical to our next step into outer space.

The satellite propulsion system would also be printed on orbit. This proposed system is the multi-mode propulsion (MMP), a concept being supported and fleshed out by AFRL. It involves sharing a fuel and oxidizer system over multiple types of propulsion. The most common are shared propulsion systems for chemical and electric propulsion system. Despite the proof of concept hot-fire tests done in 2009, funding was cut in 2010.[7] This proposal calls for an AM version of the multi-mode propulsion system. An AM version of the MMP would create the capability of a chemical and electronic propulsion system printed on orbit. Experts in the field believe a pulsed plasma, Hall thruster, or catalyst bed system would be the most likely type of electric propulsion system to be printed.

3. Technical requirements / Build time

The nominal schedule for a Hub on orbit would be ten years. This involves the parallel aspects of research being done to mature the printing technology for AM of propulsion systems in LEO, the development and design of robotics to assembly hardware on-orbit alongside the Hub design and launch mission planning to get all the needed materials into the proper orbit. An initial concept and visualization of a three module Hub can be seen in Figure 2.[8] More details of the layout and components of each module are presented later in Section V.

Figure 2: Project three module AM Hub

A fully AM printed upper stage liquid propulsion system could be a reality as soon as five years from now on Earth.[9] This is allowing development to occur at its present rate with no injection of USAF funding or research. Projection wise, it should take another five years to shift this technology up to orbit. The MMP system has a longer design time. If research was fully funded, the system could be operational in on-orbit prototype phase in the next 10 years. Nominal timelines for this research and operations can be seen in Figures 3 and 4. Remote robotics will have to develop as well to allow for the remote control of robotic arms from Earth for assembly of the propulsion system as well as attachment of the propulsion systems to the satellites after their delivery into orbit.

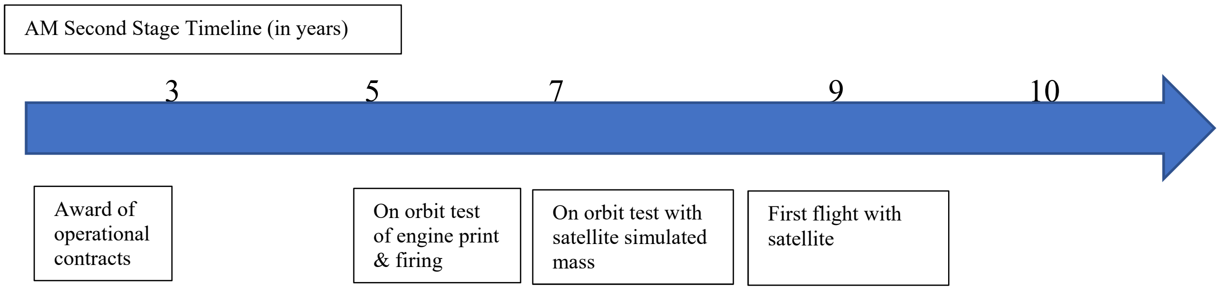

Figure 3: AM Booster Stage Timeline

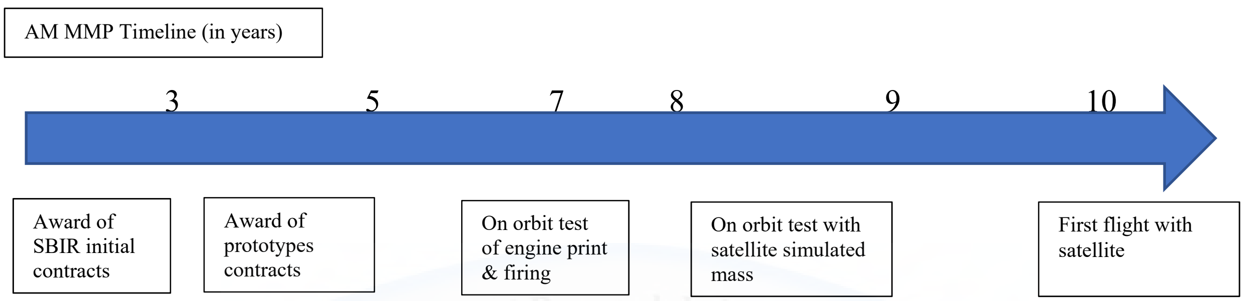

Figure 4: AM MMP timeline

A Hub design is critical to the development of printed systems on-orbit. Without it, parts could be printed, but potentially never attached to operational hardware. The design would have to include a receiving area to capture the satellite from the booster. The same receiving area would be used to receive raw materials from either the Earth, or in the future, the Moon. The Hub would also have to have a build area for the second stage boost engine as well as a build area for the multimode propulsion systems. There would also be a requirement for a tank building area to print all of the tanks required for the propulsion systems. There would be another build area for the electronics needed for the propulsion systems. Figure 5 shows a nominal timeline for the Hub research and deployment.

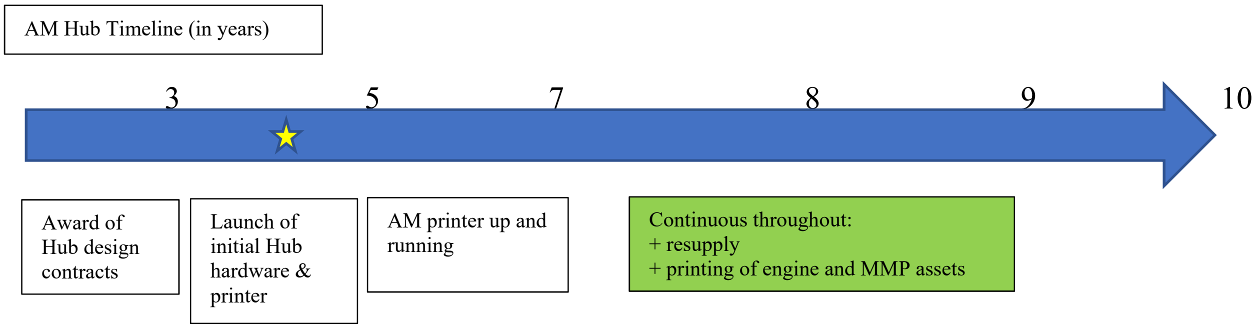

Figure 5: AM Hub timeline

4. Activities to make AM in LEO a reality

On orbit AM requires the completion of several key steps before it becomes a reality. First the plans must be laid for the AM MMP system. The relative immaturity of this system necessitates further development and testing in the university setting or government lab. While traditional MMP has been demonstrated, research related on how to print small components such as pumps and valves is still necessary. These are the most challenging components to print due to their small size, multiple rotating parts, and the high requirement for surface finishes on these rotating parts. This research is envisioned to take five to seven years. In parallel with this research would be an examination of how to print the full MMP system. At the five to seven-year point, a prototype should be ready for vacuum chamber testing. After one to two years of vacuum testing, an on orbital system will be deployed. This research effort is estimated at $20 million over a ten-year period.[10]

The other option for the MMP is to allow the technology to develop, and then leverage that technology when it is more mature. This is the cheaper option with a longer lead time and minimal level of effort on the DoD's part. This lead time is about 30 years and would most likely have a $5 million price tag at the 30-year point. There is danger here as our adversaries could take advantage of the technology or mature it faster leaving the United States out of this technology business.

The technology for printing an upper stage or second stage boost engine is much more mature. NASA, SpaceX, Blue Origin, and Aerojet RocketDyne have all printed full engines or components of engines and had full hot fires. A few examples include NASA's RS-25, SLS propulsion system pogo accumulator that has shown a 35% reduction in cost and 80% reduction in build time.[11] NASA has also printed and hot fired a RL-10 thrust chamber with a reduction in part number of 90%.[12] Aerojet RocketDyne has printed and hot fired a Bantam rocket with a thrust level comparable to one of SpaceX's reported upper stage engine.[13] Blue Origin and SpaceX have both printed components of their upper stage engines and are moving towards further printing due to the reduction in cost and parts. The company Relativity Space has made great strides in AM of rocket engines. They have hot fired their 100% AM Aeon engine 100 times at NASA Stennis. An example of their hot fire test is in Figure 6. This engine has a thrust of 19,500 pounds force which is in the same order of magnitude as the RL-10 thrust of 24,700 pounds force. The Aeon engine has specific impulse of approximately 360 seconds. A print of this engine takes 15 days and a standard rocket build is 180 days. The Aeon has 100 components while other rockets have 2700 components.[15] With this maturity, it is projected that full boost engines will be fully printed and tested on Earth in five years. The next step would be moving the printing process to orbit and testing prototypes there. If funded properly, this could be done in five years. Currently, SpaceX

Figure 6: Aeon Hot Fire[14]

is running contracts in this vein of research at the cost of $67.3 million for the SpaceX Raptor 2.[16]

Robotics is another essential piece of technology required for on orbit AM. The aerospace company Made in Space already has the concepts in place to build with robotics in space via their Archinaut system. Made in Space is also developing the External Augmentation of Generic Launch Elements (EAGLE). The EAGLE system is a recycling concept aimed at building new assemblies from old rocket parts.[17] These two concepts are critical to developing not only ways to print in space without a human in the loop, but also tackle the challenging concept of debris removal.

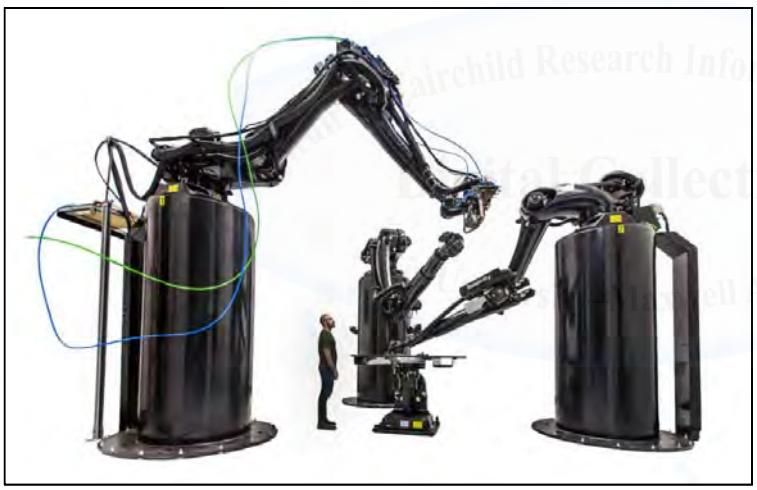

Figure 7: Robotic AM system[18]

Relativity Space also has advanced robotics AM. Their Stargate system is a set of three robotic arms designed to print a full rocket, including the propulsion system. They system can be seen in Figure 7. This robotics system has AM metal capabilities and has machine learning to improve designs as propulsion or other rocket systems mature. This is just one type of robotic system being developed for AM. Robotics is growing at a tremendous rate not only for assemble but as actual printing system. These robotic systems will allow for automated print and assemble of rocket engines on-orbit.

5. Policy / Requirements for AM Hub

The first step in building the LEO AM Hub is demonstrating its benefits for both government and commercial use in a way that inspires public/private partnership. Showing the benefits of such a partnership can cut the cost of launch and satellite deployment with an upfront investment is key. Also, these systems allow for larger payloads to placed in orbit. Next, money must be put against the plan for a nominal 10-year schedule for the upper stage and MMP as well as robotics development. Material selections must be made for the propulsion systems make-up and limits must be set for the acceptable level of divergence for in space operations. The Hub must be designed. Partners are needed for this project. Whether their partners come from private industry or are foreign friendly nations, due to the cost of this endeavor, it is critical that many space players see the value added of printing in space and move towards similar goals. Once propulsion systems are printed, there is no upper limit to what might be printed next on-orbit. This capability could easily be adapted to print full satellites or even man-rated space ships as time and technology evolve.

6. Projected Cost

Current communication satellites cost in the $300-$500 million range. An operational launch vehicle ranges in the $300-$400 million for large payloads. Best estimates put the efforts for an AM LEO Hub at $50 million in research and development and approximately $400 million for the on-orbit components with current modules in the $125 million range. This is an estimate using the BA-330 Bigelow module.[19] This is for the hardware modules at $375 million and robotics at $25 million, with the assumption that robotics is a mature technology. Launch vehicles which, at the moment, are in the $90 million for SpaceX Heavy to $350 million for the Delta IV would have to be assessed on a case by case basis. If done correctly, the future launches should cost approximately $270 million to get all Hub materials to orbit; this estimate correlates to roughly $90 million per launch using SpaceX Heavy with their reusable option.[20] AM metal printer development is developing at a rapid rate. Estimates to increase printer size are $10 million, as General Electric, Stratasys, and NASA are already printing large components. Assuming these estimates, the total cost of the AM Hub at LEO is $730 million. Even with inflation and program creep costs, this is below the cost of one standard large satellite launch and gives the United States the capability to print parts on-orbit. Resupply costs for propellant and print stock is estimated to be between $80-90 million a year. These numbers do not take into account any type of international cooperation or industry money placed towards research.

I. <u>Current concepts of Additive Manufacturing Current State & Vectors</u>

1. Metals printing

1.1 Current on Earth technology

The current technology on Earth for AM is quite extensive and diverse. There are two main types of metal printing: metal powder and wire feed. Due to the nature of microgravity in LEO, or at least until technology develops to the extent of keeping powder safe from electro-static discharge in the Hub, wire feed printing is the best option for on orbit printing. Figure 8 shows an AM wire feed system as well as photos from production runs. The metal feed stock is fed through a tight orifice and deposited on the desired print location. Depending on the style of AM, a laser, an arc-welder, or an electron beam then heats the feed wire. The metal feed wire then melts into the rest of the AM form and is bonded together.

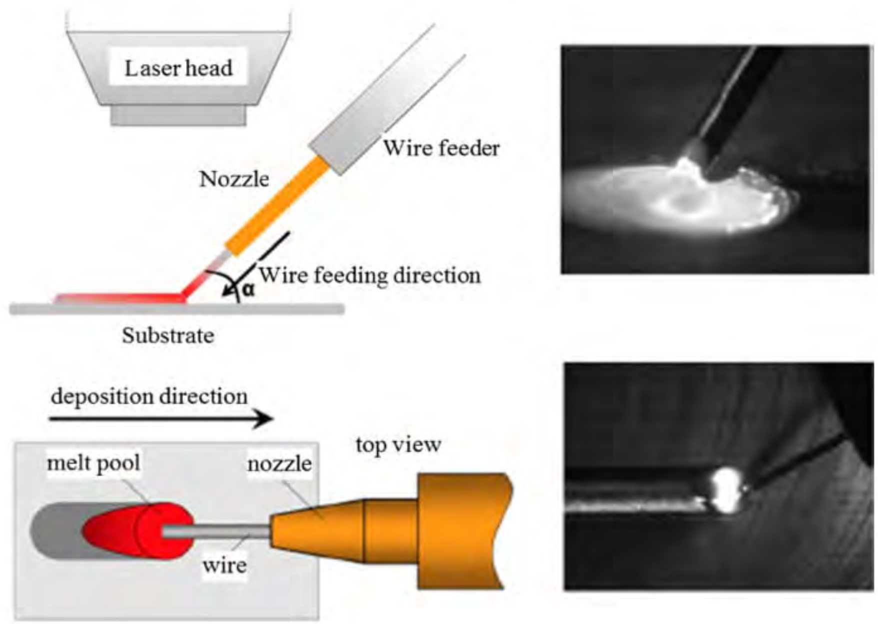

Figure 8 – Wire Feed AM[21]

1.2 Current technical challenges

Current technical challenges for printing metal for engine systems on Earth include electrostatic discharge concerns, powder removal from interior geometries, and developing material standards. Due to microgravity, powder printing systems will not be used on orbit. Therefore, material standards and void mitigation would be the focus of much of the research for in-space printing. There is a large thermal variation in space orbit. It is unknown at this time how AM parts will hold up to this sun cycling. More research into the effects of sun-cycling on AM printed metal in orbit and how to mitigate them will help reduce the impact of this risk.

Another big question at the moment is the material behavior of AM parts in space. Materials act differently in the ultra-high vacuum of space due to high pressures and strains on the metal material lattices and bonds. We are unsure how the voids in the metal lattices of AM parts will react to this vacuum. The danger with these voids is similar to outgassing with plastics. A void can build pressure with heating or large rapid pressure changes as seen in space.

If the fluid trapped in these voids expands too much, the material could be blown apart causing part failure. This line of investigation is integral to realizing AM in space and for space rating of materials.

Beyond the material science and material standards, developing system designs for printing on orbit will be critical and challenging. This is why tanks will be printed first to allow for initial systematic errors to be worked out and then continue on with printing of the more intricate parts of propulsion systems.

2. Demonstration of Metal Printing on Orbit

Currently, there are no known demonstration of metal printing on orbit. However, there are contracts let to industry partners moving in that direction. One such contract is a $10 million effort NASA awarded in late 2017 to Tethers Unlimited, Techshot, and Interlog Corp. which involves ground-based prototypes for machines capable of printing metal on-orbit.[22]

3. Future tech on orbit

Many of the needed metals for rocket engine and the MMP systems have already been developed on Earth. Many alloys such as Mondaloy 500, Inconel 625, and Ti-64 have been proven in print capacities on Earth for different rocket components such as pogo accumulators and power pumps.[23] This print capacity will have to be transferred to orbit.

Another interesting line of research to be discussed about printing on orbit, is that of electronics. Made in Space has an initial printing system called Satellite Manufacturing Machine (SMM). This system's goal is to print electronics in space. This technology and others like it should be leveraged to the fullest extent possible in order to print as many elements of a propulsion system in space to reduce the cost of lift.

II. Current launch capabilities

The current launch capabilities will be evaluated for the launch of material and as a comparison for the benefits of AM print on-orbit. The investigated systems are United States platforms only that will be available in the near term for space lift.

Lift Vehicle	Payload Mass to LEO	Cost	Booster Thrust	Booster Isp	Second Stage Thrust	Second Stage Isp
	Pounds	Dollars	MN	Sec	kN	Sec
Delta IV Heavy	62,540	$350mil	9.3	414	110	464
Falcon Heavy	140,660	$90 mil – reusable $150 mil - expendable	7.6	282	9.3	348

Table 1 - Current United States Lift Capability

Table 1 shows the launch vehicles in current space lift capability for the United States. These two platforms were chosen as they are the top class of lift for their platforms and have both launched. The Delta IV Heavy brings a tremendous launch capability of payload to the pad, but with a hefty price tag. Assessments have been done for the larger boost phase engine, as the MMP is much smaller with less mass. The dry weight of an RL-10 is approximately 277 kgs or 611 pounds dry, so the Delta IV Heavy could lift enough material for 103 engines.[24] Assuming 3% losses of material during the printing process, this is still enough material to make at least 100 upper stage engines, which would be plenty to boost satellites to higher orbits for years to come.

The up and coming Falcon Heavy, if fully demonstrated and functioning in reusable mode, would cost approximately 25% of the Delta IV and could lift enough material for 230 second stage engines. Again, accounting for 3% losses there are at least 223 upper stage engines that couple be printed on-orbit.

These engines could be printed and left in orbit as is the standard today or they could be printed and returned to the Hub. Reusability and not increasing the space debris in orbit are favorable in today's planning climate, and it is favorable to use this method. Of course, engines and their tank systems would have a life cycle when being reused. This would have to be taken into account. Current life cycles on the large boost engines are five tests before they are not considered operationally sound. Therefore, it is proposed that on-orbit boost engines will have at least five reusable boost to orbit operations before they will be brought back and evaluated for a recycle option for another engine build or a less sensitive build such as a tank.

III. Key metrics of value

1. Cost analysis

The initial upfront cost for the Hub would be substantial $730 million. However, once on-orbit, propulsion systems could be printed for second stage boost and MMP leading to a reduction in mass on satellite payloads and a reduction in mass of the second stage by all the weight of the tanks and propulsion system. As an example, the RL-10 weighs 611 pounds dry. According to recent NASA estimates, every pound sent to space costs $10,000. Therefore, with dry mass alone, it is a $6.11 million savings per launch for printing a second stage engine on orbit.[25] This is the engine itself, not even mentioning tanks or other support equipment.

2. Customers

The service of printing these engines would provide a much-needed reduction in cost of launch for all of the United States launch providers. By printing propulsion systems on-orbit, the lift capability to orbit will be greatly increased. This is because the whole second stage with its tanks and propulsion systems will be eliminated. Also, eliminated would be the tanks and propulsion system and accompanying weight for the satellite propulsion system.

3. Volume & Mass

Considering the current size of upper stage engines, a print size needs to be targeted. The RL-10 is 13.6 feet in length and seven feet in diameter with a dry weight of 611 pounds.[26] This is the most defined in open non-proprietary information for propulsion systems. The Raptor 2 has been released as having a diameter of four feet.[27] The MMP system will be smaller as the EP and smaller five-pound chemical systems needed for delta-v corrections are much smaller than boost size engines. Also, the tubing can be printed in sections and joined via robotics. Taking these sizes into consideration and adding size for robotic arms to move around the hardware, the printer size should be 15 feet by 10 feet by 10 feet equaling 1,500 cubic feet or 42.5 cubic meters. Considering the current print time of rocket components, the print and assembly time for one engine will most likely be around 24-48 hours.

IV. Proposal for in-space AM LEO Printer Hub

1. AM LEO Printer Hub

1.1 Build

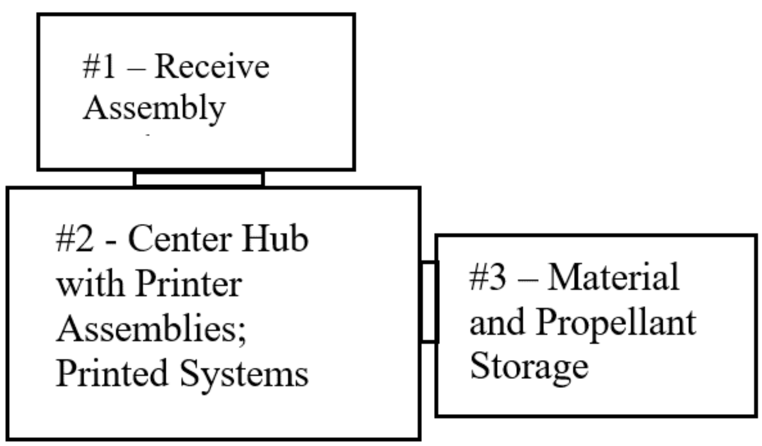

Figure 9 – Hub Diagram

The build of the Hub shall be done in a few different stages. Its nominal orbital altitude would be LEO. First, two Bigelow or Bigelow like modules will be brought up along with the robotics needed to assemble different components. Also, in the payload will be an initial metal printer and printer material for prototype testing. Robotic arms will deploy first and then the modules which will then be attached together by the robotic system. From there the rest of the modules and materials will be delivered in one more launch.[28] Propellant tanks will be printed first for simplicity. Materials and more printers will be brought up in an additional launch and restocking launches will have to occur once a year.

Figure 9 shows a nominal design of the Hub printing center. Module #1 will receive the payload from launch, attach the engine and MMP systems, and then release the satellite into it proper orientation to initiate its first delta-V burn. Module #2 is the printing area where engines will be printed and stored. Module #3 is where the raw materials and propellants will be placed for storage until they are needed.

2. Discussion of different models

Different models of development must be explored to develop this technology to see which the best route is to follow.

2.1 Commercial off the Shelf (COTS) Model: This method would be the easiest and will push development for the Hub concept into the next decade. The COTS world of AM is still developing. While an AM upper stage engine will be a reality in the near future and robotics capability is improving every day, the technology is not currently available "off the shelf" for this type of LEO AM system. If allowed to develop and mature, COTS could be used in about 25-30 years to build the proposed system on-orbit. This method would involve the USAF and commercial partners taking the lead and has an estimated bill of $10 million.

2.2 AFRL Model: The AFRL model would involve letting SIBR contracts to Universities and other businesses in the first 1-3 years of development to start the research on AM and robotics. This would then move into small scale parallel prototyping and develop into the TRL 4-6 level over the next 5 years. Finally, the program would move into operational test and have a prototype on orbit in the final 2-3 years. This research program would most likely run in the $50 million-dollar range.

2.3 DARPA Model: The DARPA model would be a fast paced and expensive development program. Technology will be developed at a fast pace. It is thought that a functional Hub system would be possible in 7 years from the start of the program. Costs for research would run higher than the other models at $100-$200 million.

2.4 Commercial Model: While not within the control of the USAF, commercial entities might decide to pursue this AM capability. This would not be ideal for the USAF as it would not have a say in many factors and interoperability of the Hub and its facilities without a cost. If done by commercial entities, the DoD and other interested parties would perhaps rent space or buy parts from the commercial vendors as they print and store them on orbit. While not inherently negative, it must be remembered that these services would be for sale for all parties. The U.S. could be made to wait for parts or could have secrets divulged while sharing print facilities with potential adversarial nations.

3. Limitations on printing on-orbit

Experts from industry and government Labs say that, the hardest piece of technology to print are pumps and valves. These are the most challenging parts to print due to the closed nature of the parts which restricts AM by-product removal as well as the micro-level precision needed for the rotating parts to operate correctly. Therefore, if it was desired to speed up the process of printing on orbit, it is recommended to remove the printing of high-speed pumps and the main propulsion valves. However, this technology will be developed on Earth in time, but it could take longer than other technology to mature.

4. Evolution of the design

Technology design is generally an iterative process. AM is no different. It will evolve and take on new roles on-orbit as it has on Earth. Printing in microgravity will be a new technical challenge with benefits. The designs for the new boost engines and MMP systems made in space will be different from those on Earth. This is because launch payloads will not have to be considered for these new propulsion systems. One must consider only the stresses of operating in space, not the constraints of multiple gravitational forces placed on a rocket during launch. This will allow for new designs possibly developing the generative design process further as the rocket engines can move towards lower weight and higher efficiencies.

5. Assembly

In many discussions, the overwhelming thought from the technical community concerning assembly on orbit for more complex parts of known propulsion systems was robotic, with the potential for "human in the loop" guidance from Earth.[29] The reason for the interest in robotic arms and assembly was that the lack of humans would allow for a much cheaper Hub. Robotics are much easier to keep functioning in space than humans. Also, it has been seen in the more recent tests on orbit in the ISS, that the humid environment required to keep humans comfortable can cause clumping with the AM feedstock as well as problems with metal deposition in the desired positions.[30] The vents and pumps required to allow for the exchange of air cause vibrations that would have to be dampened out as well. The most plausible idea is remotely controlled robotic arms by technicians on the ground. This would be a similar concept to the robotic arm on the ISS or the former Canada Arm on the STS. Robotic arms in the form of CNC machines have been proven time and time again to be precise on earth. This process would involve taking the earth-bound technology and applying it to a manufacturing process on orbit.

6. Propellants from the Moon

Initially, all propellants will come from Earth. These can be brought up in increments according to launch supply schedules. Also, any excess fuel can be drained from the first stage if it has excess fuel or if it is an expendable vehicle. In time, as the technology develops for farming of Moon elements, the Hub would benefit greatly from receiving hydrogen and oxygen from the Moon for the engine systems. The MMP chemical system would also benefit, while the rarer EP propellant requirement might be fulfilled as we learn more about the elements available in the lunar regolith.

7. Printing materials

There are two options for mining and procurement of print materials for AM on orbit. One is the Earth and the other is the Moon. Payloads of materials from Earth are immediately available as feed stock and powder are already being used for terrestrial AM. According to published data, the Delta IV Heavy can lift 62,540 pounds of payload into orbit, while the Falcon Heavy can lift 140,660 pounds to orbit.[31,32] These numbers are based off currently published lift assets and assuming a LEO Hub location. Another option is to use the current in place International Space Station supply route with the Antares system out of the Virginia Space Port. This lift capability supplies 14,300 pounds of material to orbit and costs $80 million a launch. While less capacity than a Falcon Heavy, the launch infrastructure is already in place for LEO launch, it drives the use of surplus Department of Defense motors, and the resupply mission is mature from the Virginia coast, making this option viable.[33]

The other option is a more futuristic look. It involves the mining and receiving of lunar material in the form of oxygen and hydrogen. It also would involve receiving metals from the lunar regolith. This technology would require purified LOX as well as purified LH2. These propellants would have to be filtered to the required level acceptable, removing any dangerous line blocking material. Metals from the Moon would need to be in micron powder form and then compressed into wire form for the necessary printing.

8. Launch/on-orbit capabilities improved with AM on-orbit

The idea driving the AM LEO Hub design is that second stage boost and MMP systems (tanks, avionics, etc.) will be printed on orbit. Before a system is attached to an operational satellite, the prototype will be tested on a satellite mass simulator. After successful testing, operational satellites will be flown up from the Earth's surface and the propulsion system will be attached and fueled. Then the fully integrated system will propel to its final destination. This new configuration will enable more latitude for lift and mass components. Beyond this concept, one can envision fully printed satellite systems. This is a goal for 25-50 years in the future.

V. Conclusion

The development of an on-orbit Hub for AM of propulsion systems is a technology that would change the face of space lift and propulsion development. AM on orbit will drop the cost of launch substantially, by cutting the weight of launch vehicles' second stage and payloads. To do this it is proposed the United States takes the lead in research and execution of an AM Hub for printing in LEO. Starting with printing simple items like propellant tanks, and then evolving to second stage engines and MMP systems will allow a technology base to be developed on orbit. The second stage engines will be attached to satellites coming up from Earth and used for a final boost. The MMP system will be connected and used for final maneuvering and station keeping.

The cost for the AM Hub proposal will be in the range of $500 million for the Hub and another $270 million for the launch systems to deliver the hardware into orbit. Development projects will run in parallel on three tracks. They will be development and operation of the second stage propulsion system, development and operation of the MMP system, and development and operation of the AM Hub in LEO. Restock will cost between $80-$90 million a year. In the long term, development and printing of satellites or even spacecraft will be the goal for technological advanced countries.

Appendix A: Requirements/Policy/ICD

JFSCC has a requirement for on-orbit reusable propulsion systems for upper stage boost and satellite which can be fabricated and serviced on orbit

JFSCC has a requirement to be able to additively manufacture rocket engines on orbit using terrestrial and lunar/asteroid feedstocks

JSFCC has a requirement for these engines to be able to use terrestrial and lunar propellant

JFSCC has a requirement for reusable launch to lift the Hub components into space. Resupply launches will be evaluated fiscal year to fiscal year

Notes:

[1] I wish to thank Dr. Barbara Clark, Dr. James Campbell, BGen, (ret.), Major Douglas Castonguay and Maj Kiel Martin, PhD for their thoughtful comments and suggestions. All errors found herein are my own.

[2] Saunders, Sarah, “Aerojet Rocketdyne: Successful Hot-Fire Test of 3D Printed RL10 Engine Thrust Chamber Assembly”, https://3dprint.com/170213/aerojet-3d-printed-rl10-chamber/, 5 Apr 2017.

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